A Study on the Development of a Web Based Urban Transit Reliability Evaluation System

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Over the past twenty years, the maintenance system developed, and its importance increased. For the effective maintenance, the maintenance system has been developed by introducing the concept of RCM (Reliability Centered Maintenance). This research is to develop an effective maintenance system for urban transit based on the concept of RCM. RCM is a systematic approach to develop a cost-effective maintenance strategy based on the various components' reliability of the subject system. The final process of RCM determines appropriate failure maintenance strategies. For realization of RCM, reliability evaluation framework has been studied to compute the reliability index for urban transit. The framework requires the following processes : BOM (Bill of Materials), RBD (Reliability Block Diagram) based on FBD (Function Block Diagram), and failure code classification. The goal of this paper is to define the maintenance procedure for the subject system since successful maintenance system depends on an automated maintenance plan. This plan can be scheduled effectively by collecting and analyzing data from maintenance experience. For doing this, this paper proposes the web-based maintenance system for collecting data and the computing of MTBF (Mean Time between Failures) at the maintenance stage for analyzing data.

Key Words : Reliability Evaluation, Web-based Maintenance System, Urban Transit Maintenance, Reliability Centered Maintenance, Bill of Materials, Reliability Block Diagram, Failure Code Classification

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1. Introduction

The field of urban transit has accentuated the importance of maintenance because urban transit has grown to become the principal public transportation and its defects have a great influence on safety and security to the society. The vehicle of urban transit is a complex system that consists of various electric, electronic, and mechanical equipments, and the maintenance cost of this complex and large-scale system generally occupies sixty percent of the LCC (Life Cycle Cost) (Lee, 2003). Therefore, it is imperative to cut down the maintenance cost by applying the effective method of estimating life time. At the same time, because accidents caused by the vehicle defect affect social safety and economy, it is also necessary to minimize occurrences of failure and to accurately perform maintenance tasks by investigating the cause of these repeated failures. The concept of reliability has been considered as the key to improve safety in the field of urban transit. This is called RCM (Reliability Centered Maintenance) system. Generally, reliability is defined as the 'probability that an item will perform a required function without failure under stated conditions for a stated period of time' (Garcia Marquez, 2003). The reasons for this interest may vary but often include the following objectives :

(1) Maintaining a level of functionality without a critical failure for a desired period ;
(2) Reducing cost to maintain and support the system ; and
(3) Managing safety issues due to the consequence of a failure.

Recently, RCM method has been used in many studies. Smith (1993) defined RCM as a method that determines what should need to do for operating physical equipment reliably, and presented a preventive maintenance by analyzing functional failure. Richard (1995) introduced a practical method applies to industrial field by reanalyzing the concept of RCM that Smith et al. presented. Jacobs (1998) studied a method that decreases maintenance tasks by using RCM. In the field of railway, the preventive diagnosis and the predictive maintenance for railway equipment maintenance was studied by Wada (1988). Jim August (1999) performed RCM analysis by building on a logic tree with the following contents : the definition of system function, the failure mode, the failure cause, the failure effect, the failure diagnosis, and the measure of failure.

Besides, many studies on the management system of urban transit have been done during the last decade (Lee, 2001). The information management system for railway maintenance was developed for Japan's public railroad in 1996. However, there have been problems for using the system because it is not based on reliability evaluation but just maintenance history. Similarly, London Underground Ltd. and Montreal Transit Corp. also developed management system for increasing the availability and safety of subway, which has a simple computerization system. It is difficult to judge the correct maintenance status because it just provides the historical information instead of reliability assessment. Therefore, we developed a systematic approach between information management and reliability assessment for efficient preventive maintenance environment.

In this research, a reliability evaluation framework, which is a mathematical approach, is applied. This framework uses a reliability index for RCM of urban transit. Then, this research develops a maintenance system that applies IT (Information Technology) for efficient maintenance and safety improvement of urban transit. The goal of this research is to develop the IT system that predicts life time for each component of urban transit with reliability evaluation based on historic failure. Life time can be derived from reliability assessment. That is why reliability evaluation framework to compute the reliability index is done. The framework requires four factors : BOM (Bill of Materials) (Bae, 2004 ; Lee, 2005), RBD (Reliability Block Diagram), FBD (Function Block Diagram), and standardization of failure code classification (Kim, 2004). Then, the MTBF (Mean Time between Failures) at the maintenance stage from the reliability evaluation framework can be computed. MTBF is similar to the life time of each component. In addition, it is possible to determine whether the original MTBF (Lee, 2001) is correct or not by comparing with the value of MTBF from our framework. If there is a big difference, the value of the original MTBF must be updated. The developed system defines the maintenance procedure for urban transit since successful maintenance system depends on an automated maintenance plan. This plan can be scheduled effectively by collecting and analyzing data from maintenance experience. For doing this, this paper proposes the web-based maintenance system for collecting data and the computing of MTBF (Mean Time between Failures) at the maintenance stage for analyzing data.

2. Urban Transit Reliability Evaluation Framework

For reliability evaluation using historical maintenance data of urban transit, four assumptions are established as the following in this research.

(1) Subcomponents of urban transit vehicle are mutually independent in terms of failure.
(2) All systems and its components have only two states, failed and operational.
(3) Failure is equal to Repair/exchange history data at the maintenance stage.
(4) All devices follow the random failure.

When a device in the specified level is repaired or exchanged due to the failure, the failure rate of relevant device is firstly changed by component reliability evaluation. Then, the updated failure rate is apportioned into constituent parts' failure rate with ARINC (Aeronautical Radio Incorporated) apportionment technique (Kim, 1999). Finally, the updated failure rate is brought up to the failure rates of devices located on upper levels than the relevant device. The last two processes depend on reliability relationship derived from mutual function between each device. Figure 1

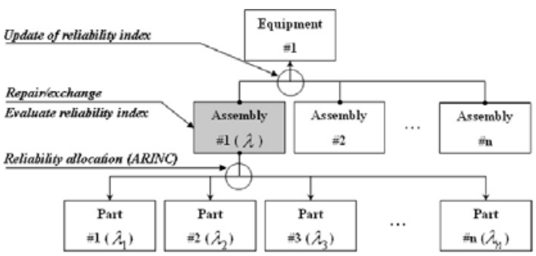


Fig. 1 Reliability evaluation framework

shows this reliability evaluation procedure.

2.1 Evaluation of component reliability

The great need for individual component reliability in complex systems is a prime consideration in system maintenance. Before system reliability improvement can be effectively carried out, it is necessary to apply available techniques for obtaining component reliability.

The failure of individual members of a group of devices in active service may be described in simple statistical terms (Jung, 2000). If n_f members of an original number η_t have failed after t hours of service, the probability of failure of a single unit in that length of time is

$$P_f = \frac{n_f}{n_t} \tag{1}$$

The probability of survival (reliability) can be written as

$$R = \frac{n_t - n_f}{n_t} = \frac{n_s}{n_t} \tag{2}$$

where

R = reliability
n_s = number of surviving members at time t.

The sum of the failure probability and the reliability totals 1 or certainty :

$$P_f + R = 1 \tag{3}$$

Random failure will produce a constant failure rate per fixed number of samples. As the number of surviving devices decreases, the number of failures per unit time will also decrease. The rate of failure is therefore proportional to the number of survivors :

$$\lambda = -\frac{1}{n_s}\frac{dn_f}{dt} \tag{4}$$

where

λ = constant of proportionality.

The constant λ can now be defined as the failure rate per unit number of survivors. It has the units of reciprocal time. Differentiation of equations (1) and (3) yields

$$\frac{dR}{dt} = -\frac{dP_f}{dt} = -\frac{1}{n_t}\frac{dn_f}{dt} \tag{5}$$

We can now equate equation (5) to relate failure rate and reliability giving

$$\frac{1}{R}\frac{dR}{dt}=-\frac{1}{n_s}\frac{dn_f}{dt} \quad (6)$$

The right hand terms of equations (4) and (6) are identical. The following expression can now be written :

$$\lambda=-\frac{1}{R}\frac{dR}{dt} \quad (7)$$

Separation of variables and integration gives

$$R=e^{-\lambda t} \quad (8)$$

Equation (8) is the basic expression for the reliability of an individual unit during its useful life. In Fig. 2 shows a complete failure-rate curve that contains the useful life period to which equation (8) applies. A term often used in reliability studies is the mean time between failures. Equation (8) can be written :

$$R=e^{-t/m} \quad (9)$$

where

m=mean time between failures (MTBF).

2.2 Evaluation of complex system reliability

For evaluation of complex system reliability, ARINC apportionment technique is applied to failure rate apportionment in this research. Because the parts of urban transit have constant failure rates, ARINC apportionment method can be used for reliability analysis.

The steps are as follows :

(1) Determination of the present sub-system failure rate.

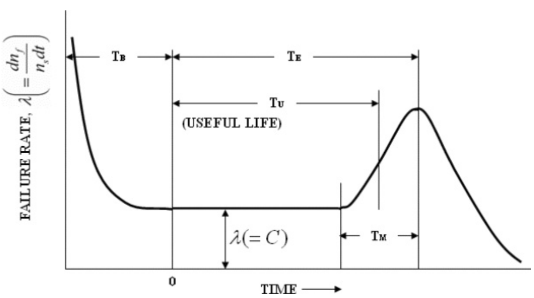


Fig. 2 Failure rate curves

(2) Computation of a weighting factor for each sub-system using the equation (10)

$$w_i=\frac{\lambda_i}{\sum_{i=1}^{n}\lambda_i} \quad (10)$$

where

n =number of subsystems
λ_i =failure rate of i-th subsystem
w_i=weighting factor for i-th subsystem.

(3) Allocation of the new sub-system failure rates using the equation (11)

$$\lambda_{newi}=w_i\lambda \quad (11)$$

where

λ =updated system failure rate
λ_{newi}=new failure rate allocated to the sub-system.

Update of failure rate towards upper level is performed according to two configurations : series system and parallel system.

In a series system which is composed of n subsystems, failure rate, MTBF, and reliability of system is calculated as the equation (12) and (13):

$$\lambda=\frac{1}{m}=\lambda_1+\lambda_2+\cdots+\lambda_n \quad (12)$$

where

λ =overall failure rate.

$$R_T=\prod_{i=1}^{n}R_i=\prod_{i=1}^{n}e^{-\lambda t}=e^{-\left(\sum_{i=1}^{n}\lambda_i\right)t} \quad (13)$$

where

R_T=overall reliability
R_i=reliability of i-th subsystem.

In the parallel system which is composed of n subsystems ; $\lambda_1=\lambda_2=\cdots=\lambda_n=\lambda_0$, where, $\lambda_i, \lambda_2, \cdots, \lambda_n$ are failure rates of th subsystems, failure rate and MTBF approximate to the following equation (14) and reliability is calculated as the equation (15) (Kim, 2003).

$$\frac{1}{\lambda}=m=\frac{1}{\lambda_0}\left(1+\frac{1}{2}+\cdots+\frac{1}{n}\right) \quad (14)$$

$$R_T=1-F=1-\prod_{i=1}^{n}(1-R_i) \quad (15)$$

where

F =unreliability function.

3. Standardizations for Reliability Evaluation

3.1 Development of BOM management system

BOM is a list or description of raw materials, parts, and assemblies that define a product (Chung, 1992). Although BOM is very important for a reliability evaluation system of urban transit, it has problems involving the size of database, inaccuracy, and flexibility. The problems are caused by using massive and flexible data to maintenance the urban transit. Therefore, it is necessary to study what minimizes database size, guarantees accurate information, and designs a flexible BOM that is influenced by a field's environment (Hegge, 1992 ; Cunningham, 1996). To solve the above mentioned problems, component technique is applied to the BOM management system of urban transit. That is the component based BOM management system. It is easy to manage the data structure in case there is a need for change of environment of data by developing the system.

Component technique (Egyed, 2000) is an application method that makes the mixture of components perform a specific function by constructing each component to have a unit function as shown in Figure 3. In other words, it is the same thing as the children's building system called Lego. Lego makes a new shape by constructing existing unit blocks, but the shape of unit blocks is not changed. Namely, if a unit block has the same interface with another block, the mixture of blocks will be able to have a new shape keeping the shape of each block. Therefore, if the interface of each component is designed like Lego, a BOM management system based on component technique can reuse data in the database and be a flexible system.

It is important to realize that managers no longer need to compose and reconstruct BOM according to working functions to maintain the urban transit (and the following is called the functional BOM). The functional BOM does not need to know about the component (equipment or part) it is going to use, its physical location, its lifetime, or its present state. In case the functional BOM needs a component, the system just asks for an equivalent component either by name or by a published identifier. Figure 4 shows the functional BOM for the light maintenance of urban transit as an example. In this case, the system constructs relevant vehicles and devices (such as arrestor, insulator, fuse and etc. of 4070 TC1 vehicle), and the manager only needs to take the information of constructed devices. At the same time, the maintenance history data is updated and preserved in the database of the master BOM for reliability evaluation.

The master BOM is the entity that is responsible for managing components and investigating

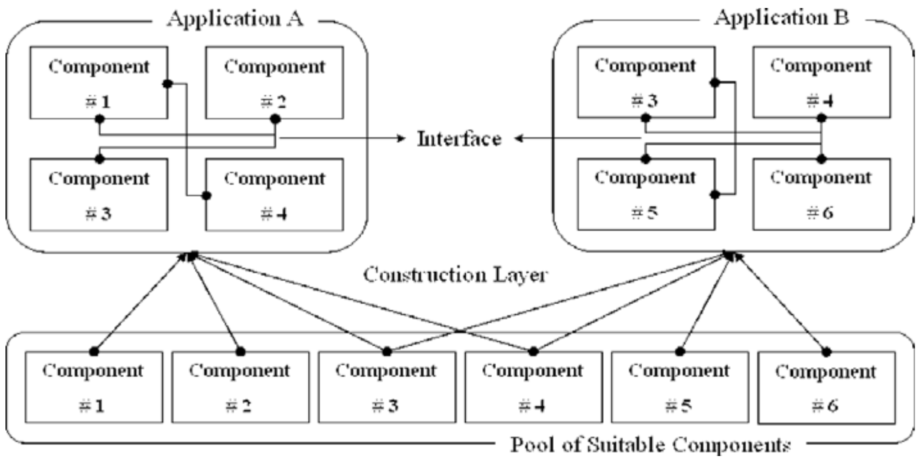


Fig. 3 Methodology of component based BOM

their physical locations and their status. Besides, constituent elements in the master BOM can interact with each other using some mediator called the rule-set. The rule-set is a group of interface rules that constructs independent components and makes the BOM system suitable and functional.

3.2 Definition of failure code classification

As one of the standardizations for reliability evaluation system of urban transit, it is necessary

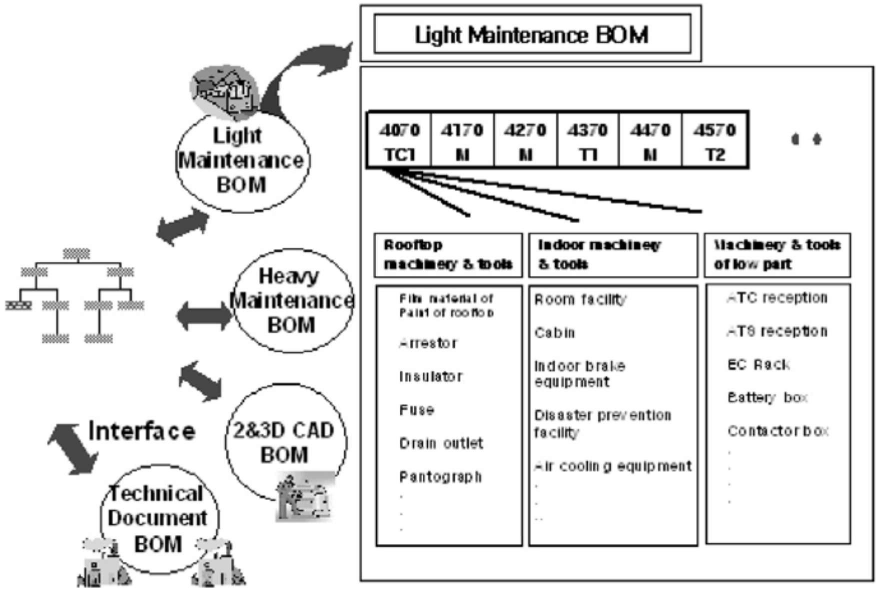


Fig. 4 Construction of the functional BOM

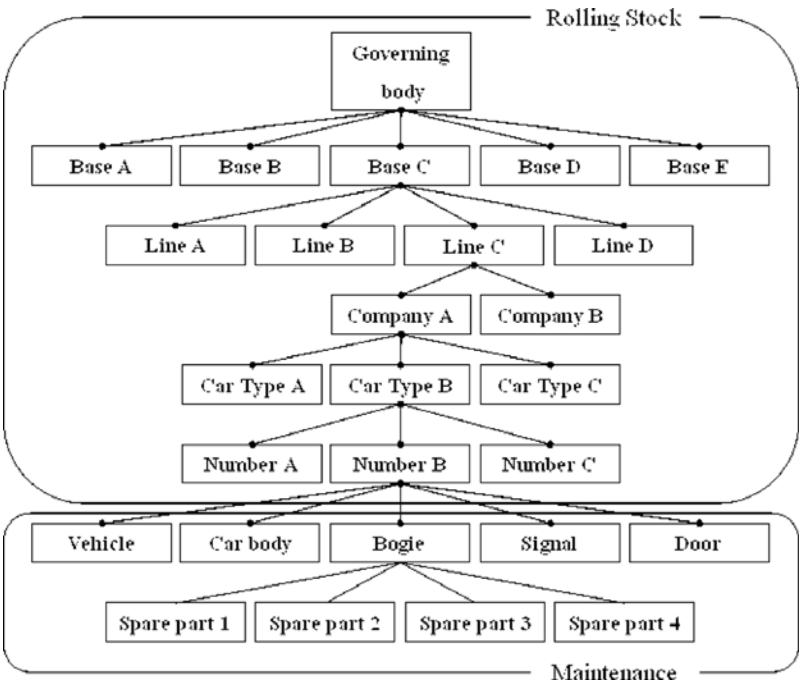


Fig. 5 Master BOM for urban transit maintenance

to classify and standardize failure codes. Failure code (Weir Bryan, 2002) illustrates the condition or reason for a failed asset. It is generally used in computerized maintenance management systems

Table 1 Rolling stock BOM

Depot	Train	Train No.	Kind of train	Company	Control form
A Depot B Depot ……	301 train 302 train 401 train ……	3001 3101 3201 3301 ……	TC T1 T2 T M	1. A Co. 2. B Co. 3. C Co. ……	1. CAM 2. CHOPPER 3. VVVF

Table 2 Maintenance BOM

1 Label	2 Label
Vehicle	◦ Vehicle Cabling ◦ Air Piping ◦ Bolt & Fastening
Carbody and Gangway	◦ Carbody Structure : Body-shell ◦ Exterior Appearance ◦ Gangway
Interior & Facility (for passenger & crew)	◦ Interior ◦ Windows Unit ◦ Exterior Equipment ◦ Cab's Equipment
Door & Door Control	◦ Passenger Door (Side Door) ◦ Cab's Door
Air Comport System (HVAC)	◦ Cooling Unit ◦ Line Flow Fan
Power Distribution & Auxiliary Equipment	◦ Static Inverter (SIV) ◦ Battery System ◦ AC & Low Voltage Equipment
Propulsion & Electric Braking system	◦ Power Supply (Pantograph) ◦ Mechanical Propulsion System ◦ Electric Propulsion System
Truck (Bogie)	◦ Bogie Frame ◦ Wheel set ◦ Primary Suspension ◦ Traction Link (Pivot) ◦ Secondary Suspension ◦ Bogie Additions
Friction brake & Pneumatic (System)	◦ Brake Control ◦ Reservoir ◦ Brakes ◦ Pneumatic Horn ◦ Compressed Air Supply
Coupler and Draft Gear	◦ Coupler ◦ Draft Gear
Lighting (System)	◦ Interior Lighting ◦ Exterior Lighting
Train Control and Monitoring System (TCMS)	◦ Display ◦ Control
Information & Communication	◦ Train communication (Radio) ◦ Information & communication (PIS, PA)
Signal	◦ ATC/ATO

(Mullen, 1993). However, to get the wide usefulness, like being able to express various or complex failure modes, it should be expanded. Expanded failure code, which includes data of maintenance history, classification of failure, and the reason of failure mode, etc., makes it possible to gather data and standardize maintenance work.

Current failure data and classification in work space must be analyzed for standardizing failure codes. Table 3 shows the sample data for current failure classification. As a result of these analyses, a standardized classification rule and code numbering system in terms of failure are made like Fig. 6. The expanded failure code is an eight-position pattern and consists of five items : failure classification, mid-class, failure modes, failure causes, and severity. Failure classification level means fourteen main subsystems of urban transit and mid-class level shows devices that belong to lower level of fourteen main subsystems on the master BOM. Severity, an assessment of how serious the effect of the potential failure mode, is a kind of weighting factor that gives the priority of maintenance to the relevant device.

When failure occurs in a vehicle of urban transit, the expanded standard code makes the system take it as input data for calculating the reliability index, and the users can take it as a standardized procedure of maintenance.

3.3 Construction of RBD

RBD (Wendai Wang, 2004) has been used as a practical reliability modeling method for industrial and commercial power systems. It is a graphical presentation of a system diagram in reliability-wise or functional logic ; i.e., connecting subsystems or components according to their function or reliability relationship. A block physically represents a component or subsystem. The logic diagram is arranged to indicate which combinations of component failures result in the failure of the system, or which combinations of components working properly keep the system operating.

This paper, first, analyzed the functional logic of components that is on BOM of urban transit and made up FBD that expresses the functional behavior of the system. Also, this paper constructed RBD after grasping the reliability relationship of each component on basis of this FBD. For example, Fig. 7 illustrates the total RBD system of urban transit. Each subsystem of urban transit performs an important function to support the service of operation normally. In case a failure occurs in one out of fourteen subsystems, it is impossible that the vehicle support the service of operation normally. Therefore, each subsystem

Table 3 Current failure classification

Failure classification	Failure mode	Actions taken
CM	CM inventor failure	PCB rack exchange in CMSB box
CM	CM NG	CM oil replenishment & air filter exchange
BRAKE	CM failure	Lead line exchange to PTR
BRAKE	CM valve discharge	CMG failure, exchange
BRAKE	CM air dryer leakage	Wing valve fracture in dryer, exchange
BRAKE	CM inventor failure display	CM oil replenishment

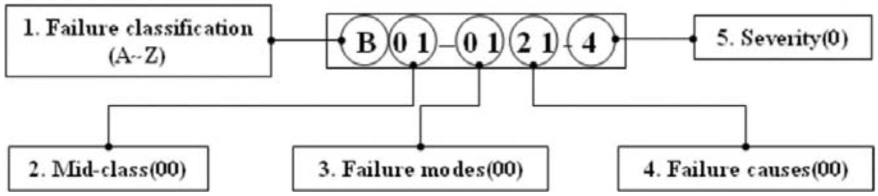


Fig. 6 Failure code indexing order

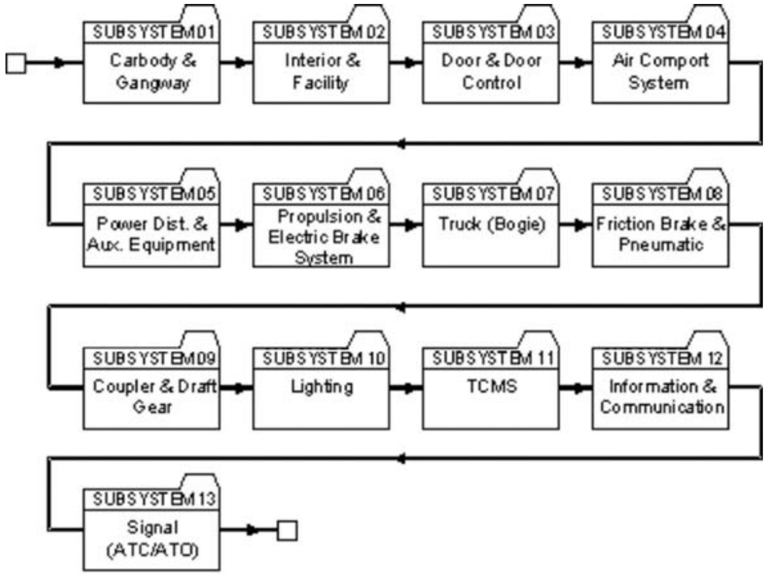
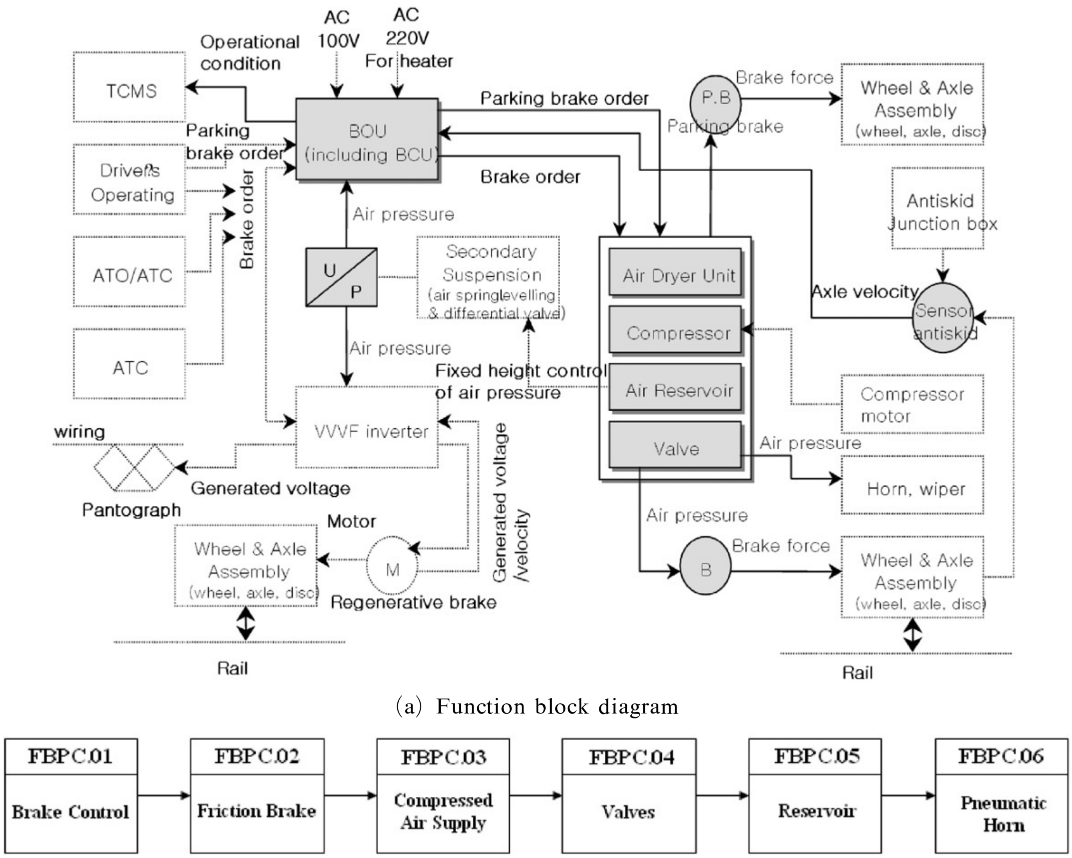


Fig. 7 Urban transit total RBD



(a) Function block diagram

(b) Reliability block diagram

Fig. 8 FBD and RBD of FBPC system

is not a parallel but a sequential relationship from reliability viewpoint. Figure 8 shows FBD and RBD about FBPC (Friction Brake & Pneumatic Control) system as a sample out of fourteen subsystems. There are generally five kinds of braking in urban transit. Those are common braking, emergency braking, security braking, stoppage braking, and parking braking. For these five kinds of braking, urban transit brake system use two control methods. One is electric braking control method using electric propulsion system and inverter, and the other is friction braking control method using contact resistance between brake disc and brake pad. In case of normal condition, electric braking control method is mostly applied to urban transit braking. In case urban transit is below proper velocity or electric braking power is insufficient, friction braking control method is applied to urban transit braking. This fiction braking control method uses FBPC system. FBPC system is a kind of braking device, which makes urban transit stop or maintains the status by using air (Lee, 2001). As illustrated in Table 2, it has 5 parts: brake control, air compressor, friction brake, reservoirs, and valves. FBD and RBD of FBPC system are shown respectively in Fig. 8. Figure 8(b), RBD of FBPC system, shows a series structure of each subcomponent because each failure affects the braking performance of urban transit.

4. Application

This chapter deals with reliability indexes and its analysis method for reliability assessment of a system. Predicted life time and failure rate is verified with those calculated by the application program (Relex Software Co., 2002) for reliability estimation.

4.1 Sample model definition — Friction Brake & Pneumatic System

This paper takes FBPC system as a sample model to develop reliability evaluation system. For reliability evaluation of FBPC system, first of all, modeling of FBPC main devices have to be performed by constructing FBD and RBD which symbolize relationship of each part. Then, established historical data is analyzed into relevant part, operating time, occurrence, failure mode, failure cause and severity. Finally, reliability index can be calculated by using reliability evaluation framework and failure rate data of parts.

As shown in Figure 8, because parts of FBPC system have a relationship in a series of system, the failure rate of FBPC system is calculated by the following equation (16).

$$\lambda_{BRAKE}=\lambda_{BC}+\lambda_{OP}+\lambda_{FB}+\lambda_{RS}+\lambda_{VV} \qquad (16)$$

Where

λ_{BC} =failure rate of brake control
λ_{OP} =failure rate of air compressor
λ_{FB} =failure rate of friction brake
λ_{RS} =failure rate of reservoirs
λ_{VV} =failure rate of values

(1) Brake control λ_{BC}: Brake control includes not only BOU (Brake Operating Unit) but also controllable parts, which secure the power of braking for urban transit. BOU is controlled by an electric signal. When braking in common or emergency is worked on/off, BOU controls whether reservoirs is filled up or emptied by air. BOU is composed of valves and electronic units, which control braking in common through, cross branding of vehicle. Electronic unit is control board which is composed of electric/electronic parts. This paper shall omit the modeling for prediction of its failure rate because of duplication of model for electric/electronic part in MIL-HDBK-217F.

(2) Friction brake λ_{FB}: For decrease or stop of a vehicle, it is necessary to convert kinetic energy into heat energy. Friction brake is a device which absorbs or gives out this heat energy. Friction brake is composed of actuator, spring, friction materials, bearing, seal, and housing. The modeling for prediction of failure rate is illustrated in equation (17)

$$\lambda_{FB}=\lambda_{AC}+\lambda_{SP}+\lambda_{FR}+\lambda_{BE}+\lambda_{SE}+\lambda_{HO} \qquad (17)$$

Where

λ_{AC} =failure rate of actuator
λ_{SP} =failure rate of spring
λ_{FR} =failure rate of friction materials
λ_{BE} =failure rate of bearing

λ_{SE} =failure rate of seal
$_{HO}$ =failure rate of housing

(3) Reservoir λ_{RS} : the failure rate of reservoir is calculated as the equation (18).

$$\lambda_{RS}=\lambda_{SE}+\lambda_{SP}+\lambda_{PC}+\lambda_{VA}+\lambda_{CW} \quad (18)$$

Where

λ_{SE} =failure rate of seal
λ_{SP} =failure rate of spring
λ_{PC} =failure rate of cylinder interface
λ_{VA} =failure rate of valve
λ_{CW} =failure rate of cylinder wall

(4) Valve λ_{VV} : Generally, there are a poppet type and sliding-action type in a valve. A poppet type valve is utilized for controlling flow, pressure, direction of fluid. A sliding-action type valve is utilized for distributing uniform pressure of fluid.

The failure rate of poppet type valve can be written in equation (19).

$$\lambda_{VV\_PO}=\lambda_{PO\_B}\cdot C_P\cdot C_Q\cdot C_F\cdot C_v\cdot C_N\cdot C_S\cdot C_{DT}\cdot C_{SW}\cdot C_W \quad (19)$$

Where

λ_{PO_B}=basic failure rate of poppet type valve
C_P =pressure factor of fluid
C_Q =factor of air leak
C_F =factor of surface disposal
C_v =factor of temperature/lubrication
C_N =factor of pollution level
C_S =factor of seat stress
C_{DT} =factor of seat diameter
C_{SW} =factor of seat land wide
C_W =factor of flow rate

The failure rate of sliding-action type is calculated in equation (20).

$$\lambda_{VV\_SV}=\lambda_{SV\_B}\cdot C_Q\cdot C_v\cdot C_N\cdot C_B\cdot C_{DS}\cdot C_v\cdot C_\mu\cdot C_W \quad (20)$$

Where

λ_{SV_B}=basic failure rate of sliding-action type valve
C_μ =factor of friction
C_B =factor of spool clearance
C_{DS} =factor of spool diameter

4.2 Result of reliability prediction and verification

Desired reliabilities are introduced based on

Table 4 Desired and calculated reliabilities of urban transit

Subsystem	Desired		Calculated		
	MTBF (hours)	Ratio (%)	MTBF (hours)	Ratio (%)	Failure Rate ($\times 10^{-4}$)
Vehicle Cabling/Piping	-	-	-	-	-
Carbody & gangway	46,000	0.25	-	-	-
Interior & facility	767	15.0	-	-	-
Door & door control	719	16.0	719	28.92	13.91
Air comport system (HAVC)	1,554	7.4	3,133	6.64	3.19
Power distribution & aux. equipments	1,173	9.8	3,212	6.47	3.12
Propulsion & electric braking system	1,513	7.6	4,231	4.91	2.37
Truck (bogie)	3,710	3.1	-	-	-
Friction brake & pneumatic system	898	12.8	1,029	20.21	9.72
Coupler & draft gear	14,375	0.8	16,667	1.25	0.6
Lighting (system)	-	-	-	-	-
Train Control & Monitoring system	3,485	3.3	4,472	4.65	2.24
Information & communition	685	16.8	973	21.4	10.28
Signal (ATC/ATO)	1,608	7.15	3,811	5.45	2.63
Total (unit)	**115**	**100**	**208**	**100**	**48.06**

standard that is managed at the maintenance stage. Then, actual reliabilities using the reliability evaluation method is predicted. Finally, this paper compares a desired reliability with a predicted reliability and estimates the result. In case a device typically follows random failure, the reliability index can be considered as MTBF (Mean Time between Failures), MDBF (Mean Distance between Failures), MTBSF (Mean Time between Service Failures), and MDBSF (Mean Distance between Service Failures). MTBF out of these indexes is considered as reliability standard of each device in developed reliability evaluation system. Desired MTBF (Lee, 2001) is derived from current maintenance standard. Under the current maintenance standard, the MTBF of a vehicle requires 115 hours. This paper allocated the desired MTBF of a vehicle to the MTBF of fourteen subsystems by applying ARINC method. Table 4 shows the desired MTBF of fourteen subsystems.

By doing reliability analysis based on failure historical data of FBPC system, the results as shown in Table 5 and Fig. 9 are obtained. In Table 5, the MTBF of 2058 hours is the result per one unit of FBPC system. Because one unit of FBPC system is equipped in two vehicles, the MTBF of FBPC system becomes 1029 hours per vehicle. This result demonstrates that the MTBF of 1,029 (hour per vehicle) meets the desired MTBF of 898 (hour per vehicle) in Table 4. Besides, for verifying propriety, the MTBF of FBPC system was calculated by an application program, relex

Table 5 FBPC system reliability and verification

Subsystem	Developed system		Relex		Error (%)
	Failure rate ($\times 10^{-6}$ hour)	MTBF (hour-Unit)	Failure rate ($\times 10^{-6}$ hour)	MTBF (hour-Unit)	
Brake Control	202.2	4,946	195.9	5,104	3.21
Valves	106.9	9,355	104.4	9,578	2.39
(Friction) Brake	122.6	8,157	117.0	8,547	4.78
Air compressor	8.0	125,000	7.9	126,908	1.52
Reservoir	20.6	48,544	20.3	49,261	1.47
Pneumatic horn	25.6	39,063	25.2	39,682	1.58
Total(unit)	**485.9**	**2,058**	**470.7**	**2,124**	**3.23**

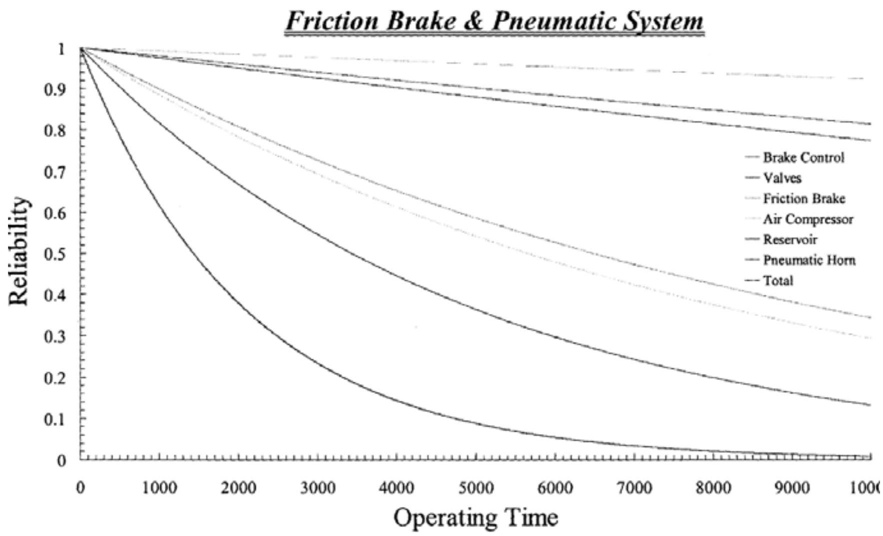


Fig. 9 Reliability index versus operating time of FBPC system

7.0, with same input data and Table 5 shows the result. As shown in Table 5, the application program shows that the failure rate is 470.7×10^{-6} and the MTBF is 2,124 hours, and developed system shows that the failure rate is 485.9×10^{-6} and the MTBF is 2,058 hours. The total error is 3.23%. Therefore, it is reliable as much as the error is below five percent. By applying this reliability analysis repeatedly to fourteen subsystems of urban transit, this paper obtained MTBF and failure rate of each subsystem and illustrate in Table 4. The result shows that the MTBF of 208 hours meets the desired MTBF of 115 hours in terms of urban transit vehicle.

4.3 Failure mode effect analysis (FMEA)

Generally, FMEA is defined as the 'procedure and tools that helps to find all potential failure modes of a system or components, to check and to evaluate its effect on other sub-system and on the required function of the system'. Through FMEA, failure modes, which have a serious influence on the entire system, can be identified and ranked. In this research, we had applied a failure grade method for FMEA (Song, 2005).

Each failure mode gets a numeric score that

Table 6 Relationship between failure grades and failure ranks

Failure rank	Failure grades (C_s)	Failure classification
I	7～10	Critical failure
II	4～7	
III	2～4	
IV	Below 2	
Major failure	Minor failure	Negligible failure

Table 7 Severity classification

Level	Severity	Definition	C_1
1	Catastrophic	Major system damage/loss — impossibility of attainment of mission	10
2	Critical	Partial system damage — interruption of attainment of mission - attainment of mission by using supplementary means	7
3	Marginal	Minor system damage — interruption of attainment of minor mission - attainment of mission by using supplementary means	4
4	Negligible	Minor failure — have no effect on mission	1

Table 8 Occurrence classification

Level	Severity	Definition	C_2
1	Frequent	A single failure mode probability is greater than 0.20 of the overall probability of failure during the item operating time interval.	10
2	Probable	A single failure mode probability is more than 0.10 but less than 0.20 of the overall probability of failure during the item operating time interval.	7
3	Occasional	A single failure mode probability is more than 0.010 but less than 0.010 of the overall probability of failure during the item operating time interval.	5
4	Remote	A single failure mode probability is more than 0.0010 but less than 0.10 of the overall probability of failure during the item operating time interval.	3
5	Improbable	A single failure mode probability is less than 0.0010 of the overall probability of failure during the item operating time interval.	1

Table 9 FMEA sample results of FBPC system

Mode	Result of FMEA			
Piston sticking	Cause	Contamination		
	Effect	Output of low pressure		
	Severity	1	Occurrence	2
	C_s	8.366	Failure rank	I
Spring fracture weakening	Cause	Contamination		
	Effect	Output of low pressure		
	Severity	3	Occurrence	2
	C_s	5.916	Failure rank	II
Bleeder valve sticking	Cause	Contamination		
	Effect	Exhaust of unsuitable gas		
	Severity	4	Occurrence	2
	C_s	2.645	Failure rank	III
Lining weakening	Cause	Aging/heat		
	Effect	Poor contact between exposed steels reducing of arresting capacity		
	Severity	2	Occurrence	2
	C_s	7	Failure rank	I

quantifies the likelihood that the failure will occur and the amount of harm or damage, which the failure mode may cause, to a person or to equipment. Namely, a failure grade is a mathematical product of severity and occurrence. According to these scores, failure modes are classified into four failure ranks as shown in Table 6. A failure grade is calculated as following equation (21).

$$C_s = (C_1 \times C_2)^{\frac{1}{2}} \quad (21)$$

Where,

C_s =failure grade

C_1, C_2=grades of severity and occurrence respectively

Such grades of severity and occurrence are based on MIL-STD-1629A as shown in Tables 7 and 8, respectively. All failure modes are ranked from I to IV according a failure grade as shown in Table 6. Table 9 shows results of FMEA of Friction Brake and Pneumatic system. The 'piston sticking' whose a failure rank is I, must be classified as a critical failure and given priority to schedule repair or inspection plans. Also, the countermeasures for this potential failure also must be established.

5. Development of Web-Based Maintenance System

The construction of BOM and the standardization of failure code classification system had been done in advance. Also, we had performed reliability evaluation based on failure historical data. Through a series of process above, we had developed web-based maintenance system to predict life cycle. Such a web-based system has advantages as follows :

(1) Collection of easy and quick failure historical data ; and

(2) Real time response of information related with repair.

5.1 System architecture and database design

The framework of the developed system is as follows. Out of devices having a low reliability, the high failure rank device due to a result of FMEA, is reflected to establish maintenance plans above all. Through registration of failure historical data, the reliability indexes and the results of FMEA are updated. Such a process being repeated continuously, more accurate life time and failure rank can be gained. Also, the developed system is made up so that workers can refer to the expert system for procedures of a failure diagnosis and a repair. Therefore, maintenance system consists of a failure management module, a preventive maintenance module, and an expert module.

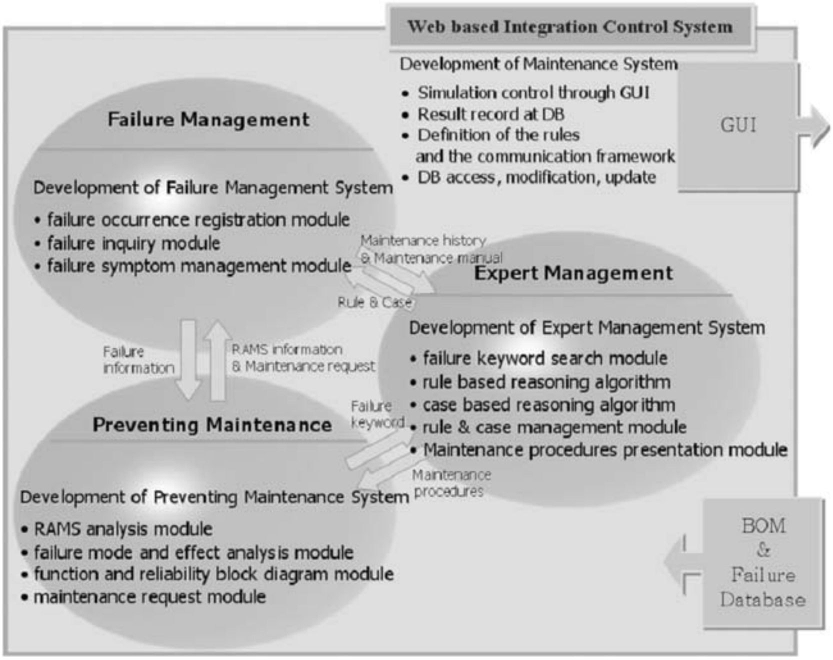


Fig. 10 Architecture of developed system

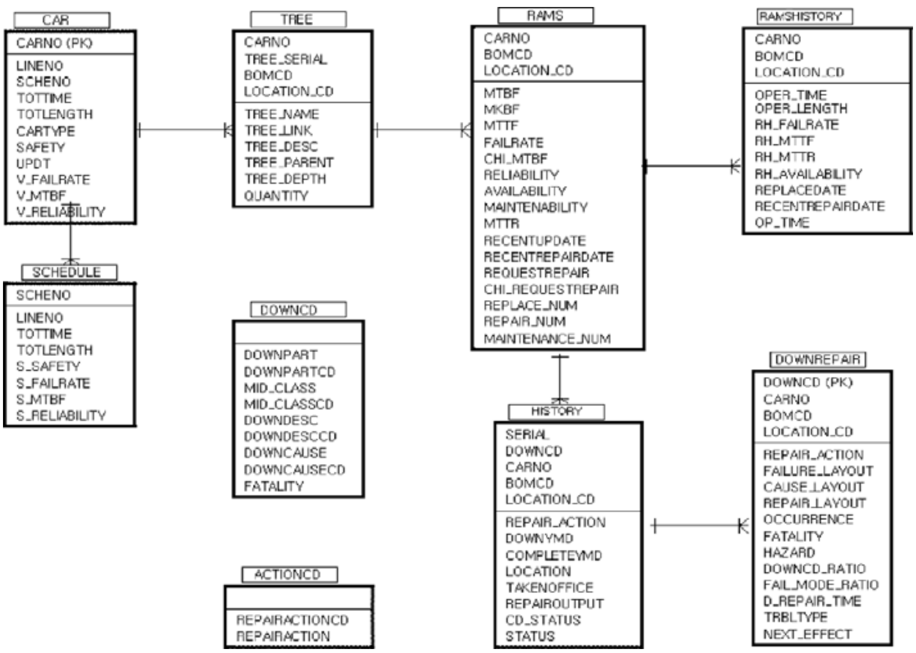


Fig. 11 Entity Relationship Diagram of database

The architecture is shown in Fig. 10. The development environment is as below :

- Web-based Applications ;
- Web Tier development environment : JSP+ Java ;
- Development programming language : JDK 1.3.1_06, J2SDEE 1.3.1 ;
- Database : Oracle 9i ; and
- WAS : WebSphere.

A database was constructed so that it can easily and quickly be accessed, updated and extended. Entity Relationship Diagram is illustrated in Fig. 11. RAMS table has results of reliability analysis. RAMSHISTORY table contains historical data of reliability analysis and these data are used for graphing failure rate, MTBF, reliability indexes and MTTF (Mean Time to Failure). DOWNREPAIR table includes results of FMEA. DOWNCD table is for failure codes. CAR table has basic information according to car number, vehicle number and line number of the urban transit. In the HISTORY table, maintenance history is accumulated, and the TREE table contains information to the hierarchical tree of BOM. To uniquely store, process and retrieve every possible data for the table, we set car number, BOM code and position number as Primary Keys.

5.2 Modules and graphic user interface of maintenance system

Web-based maintenance system developed in this research consists of a reliability analysis module by parts, a reliability analysis module by cars and vehicles, FMEA module and a repair request module.

(1) Reliability analysis module by parts

This module displays failure rate, MTBF, reliability, availability and maintainability of systems, sub-systems, equipments and parts by line number, vehicle number and car number of urban transit. Through graphs, changes of these indexes according to free operating time can be checked. The

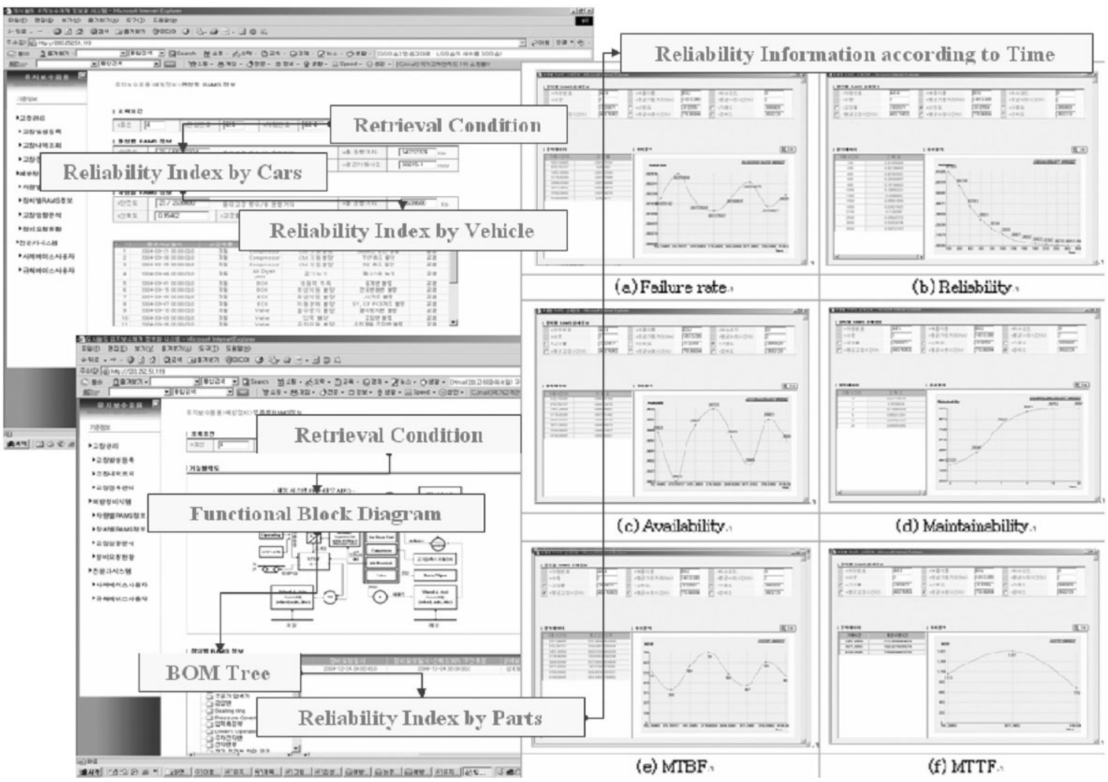


Fig. 12 Reliability analysis modules by cars, vehicles and parts

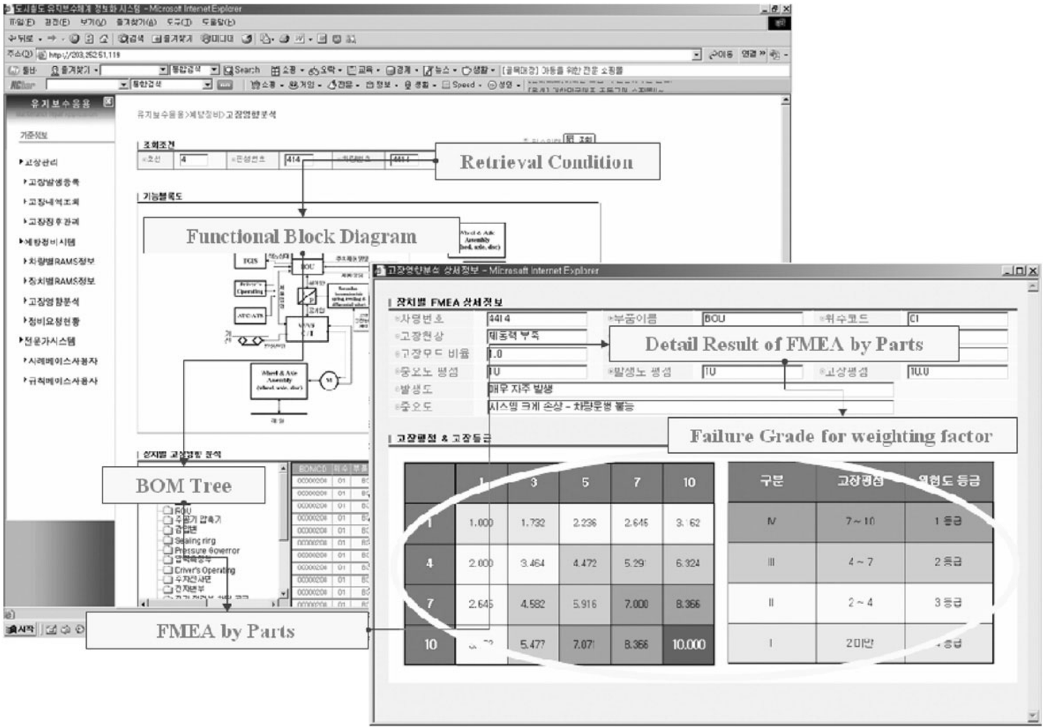


Fig. 13 FMEA modules

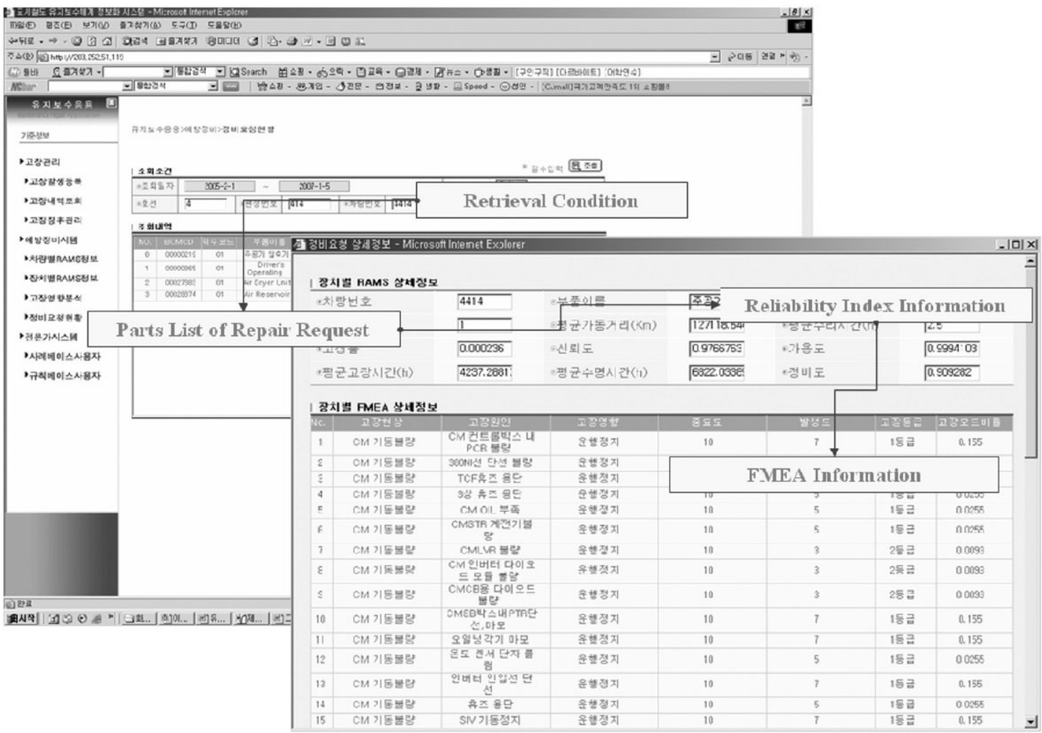


Fig. 14 Repair request module

GUI (Graphic User Interface) is shown in Fig. 12.

(2) Reliability analysis module by cars and vehicles

In this module, safety and major accidents which so far occurred by cars and vehicles can be read, where major accidents mean failures whose failure rank is I. The GUI is as the following Fig. 12.

(3) FMEA module

In this module, failure modes, failure causes, actions taken, failure ranks, next effects and so forth by equipments and parts can be identified. Namely, when equipments are out of work, this module provides information related with failures which those have. The GUI is illustrated in Fig. 13.

(4) Repair request module

Repair request module gives a list of parts whose life cycle is due and reliability indexes and FMEA results related with these. The principle of repair request is that through reliability analysis and FMEA, out of equipments whose life time expires, equipments whose exert critical effects on the entire system must be first requested. Besides, the procedure of the repair by linking with the expert system can be referred. The GUI is designed as Fig. 14.

6. Conclusions

This research predicted the life time of each urban transit device with historic failure and applied a web technology to this evaluation program. As the result, the developed system came to give a manager the information for efficient maintenance and safety improvement. From construction of maintenance system for urban transit, this paper obtained the following conclusions.

(1) In this paper, component technique was applied to design the structure of database. Then, the functional BOM was derived from the master BOM according to rule-set. Hereby, when the data structure requires changing, the management system can enhance the flexibility because the relevant rule-set just needs to be changed. In addition, information of materials (such as frequency of use, standard, amount of redundancy, and plan of maintenance) can accurately be obtained. Finally, a unique device that feeds historical failure data into reliability evaluation system can be defined.

(2) This paper provided standardized failure code classification that can be used commonly by analyzing the failure data that each maintenance base has gathered indiscreetly. By constructing failure code data (such as failure mode, cause, related device, and measure) as directory structure and by matching BOM material code with failure code, the history of failure device can be managed. This history can predict the life cycle of relevant device.

(3) This paper analyzed the functional logic of components that is on BOM of urban transit and made up FBD that expresses the functional behavior of the system. Finally, this paper has constructed RBD after grasping the reliability relationship of each component on basis of this FBD. Hereby, all reliability indexes of urban transit are obtainable by using reliability evaluation framework in chapter 2 and constructed RBD.

(4) For predicting the life cycle of a system, a reliability analysis method about complex system was introduced. Then, this paper compared the desired MTBF under maintenance standard of urban transit with the calculated MTBF using developed program. In case of FBPC system, the result showed that calculated MTBF of 1029 (hour per vehicle) meets the desired MTBF of 898 under the maintenance standard of urban transit. Through comparison with failure rates using the application program, this paper verified that the developed system is reliable because the result has errors of less than 5 percent.

(5) A failure grade method for FMEA was introduced. The criterion for grades of severity and occurrence was based on MIL-STD-1629A. This paper also performed FMEA, taking FBPC system out of fourteen subsystems as a sample model. As the result, the failure rank of a failure mode, 'piston sticking' was I, a failure cause was 'contamination' and the next effect which this failure mode exerts on the entire system, was 'output

of low pressure'

(6) For gathering easily and quickly failure historical data a maintenance system was developed on basis of web. The developed system consists of reliability analysis module, FMEA module and repaired request module. The outline of developed system is that a low reliability and the high failure rank devices are reflected to establish maintenance plans above all. Also, it is constructed so that reliability index, failure modes, failure causes, next effect and so forth can be displayed.

The successful maintenance system would reduce unnecessarily the number of repeated repair/inspection and present countermeasures against failures which will occur in the future. This will not only cut down operating and maintenance cost of urban transit, but also makes a contribution to raise public confidence.

Acknowledgments

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